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Exploring the Accuracy of the North American Mesoscale Model during Low-Level Jet Influenced Convection in Iowa

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ABSTRACT

This study analyzed low-level jet (LLJ) influenced overnight convection cases over Iowa. There are two main regimes for LLJ development over the Great Plains. One is when there is an upper-level trough in the western United States, while the other is dominated by an upper-level anticyclone. The forecasts of the twelve kilometer North American Mesoscale model (NAM) were analyzed for accuracy in both regimes and overall. The variables examined were the LLJ peak magnitude, timing, location, and total rainfall produced in Iowa from 0000UTC-1200UTC the day of an event. Although weak underforecasting was found regarding the magnitude of the LLJ with both models, there were no significant shortfalls regarding magnitude, timing, or location for either regime. However, the model runs significantly underforecasted the magnitude and area of rainfall, as all but one model run produced a rainfall maximum that was underforecasted in both LLJ regimes.

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1. Introduction

The weather over the Great Plains of the United States has been an emphasis of studies for many years. There are a multitude of things that impact precipitation on the Great Plains. From the advection of moisture from the Gulf of Mexico, to the late-summer monsoon conditions over the southwestern United States with the coupled Bermuda High that forms in the southeast, it is important to be able to understand and be able to accurately forecast precipitation.

One of the processes that helps to spark precipitation over the Great Plains is the formation of the nocturnal low-level jet (LLJ). The LLJ helps to transport warm and moist air northwards, and can lead to precipitation through low-level convergence as well as frontal overrunning (Chen and Wang 2009). Unlike conventional thought, the precipitation produced by the LLJ occurs at night, in the absence of daytime heating and convection, so it is important to be able to understand how this process works. Due to this, there have been a plethora of studies aimed at describing how the LLJ forms and its impact on precipitation over the Great Plains of the United States.

It is extremely important to not only understand how the LLJ forms, but also be able to accurately forecast it. Many forecast models have a tendency to underrepresent precipitation totals during LLJ events. Therefore, the goal of this study was to analyze the effectiveness of the North American Mesoscale model (NAM) on forecasting the timing, location, and magnitude of the LLJ, as well as forecasted precipitation over the state of Iowa.

2. Background

a.) Low-Level Jet Formation

The LLJ is an extremely common meteorological feature experienced in the Midwest during the spring through early fall. This feature is especially prominent for the state of Iowa, as the LLJ often helps to supply moisture and convergence for overnight precipitation. The low-level jet is a feature that forms typically around sunset. As the sun sets, there is a large amount of radiational cooling over the land. This leads to a stable layer near the surface, which helps the boundary layer to stabilize and decouple from the surface (Loeffelbein 2008). As a result, all of the friction that the surface imposes will also no longer effect the wind pattern. When the wind is no longer affected by the frictional component, the air parcels are able to accelerate much faster (Federovich and Shapiro 2010).

The LLJ will reach its peak strength in the early morning (~0600UTC-0900UTC), and will begin to weaken once the sun rises, the boundary layer begins to mix, and surface-based friction returns to the system (Federovich and Shapiro 2010). Throughout the night, there is an inertial oscillation of the LLJ as the Coriolis force turns the winds to the right in the northern hemisphere. The maximum intensity occurs when the Coriolis force turns the winds enough so that they align with the geostrophic winds, resulting in super-geostrophic flow (Loeffelbein 2008). Once friction returns to the system due to daytime mixing, the winds weaken from geostrophic overnight to sub-geostrophic during the day. The low-level jets that are formed through this process will be the driving force for the precipitation studied in this research.

b.) LLJ Impact on Precipitation

Throughout the spring and summer months, the low-level jet has a big impact on overnight convection throughout the Great Plains. According to case studies performed by Arritt et. al (2005), the average direction of the low-level jet is south or southwest, which is about 75% of all occurrences. The other 25% of LLJ’s have a northerly component. The direction of the LLJ is extremely important because of the type of air that it advects into the Great Plains. The southerly LLJ helps to bring warm and moist air northward, from the Gulf of Mexico in particular (Arritt et al 2005). This movement of water vapor is extremely important in producing overnight precipitation because this advection will create a moist and unstable environment capable of producing rainfall (Chen and Kpaeyeh 1992). The low-level jet supplies about one-third of the total water vapor over the Great Plains in the spring, so it is extremely important to understand how this process works, as well as being able to accurately forecast the rainfall that results from it (Chen and Wang 2009).

Once the LLJ transports in the warm air and water vapor, the LLJ can help to form precipitation. One way is frontal overrunning, where the LLJ can override a front already in the region, which can help lead to convection (Chen and Wang 2009). Another is that there can be increased convergence at the "nose" of the LLJ, where the fast speeds on the northern side of the jet run into the slower winds outside of the jet. This helps to create convergence near the surface, and upward motion as a result. It is important for models to be able to handle these different methods of precipitation production, and failure to do so will result in less accurate forecasts during LLJ events.

c. LLJ Synoptic Regimes

During the spring and into the late summer, there are two major synoptic regimes that correspond to low-level jets over the continental United States (Chen and Wang 2009). The first type includes an upper-level trough to the west of the LLJ, with a slight ridge to the east. The second regime consists of a large ridge over the west/central United States. These different synoptic setups were characterized by Chen and Wang (2009), with the upper-level trough environment denoted as "C-type LLJ's" and the upper-level anticyclone environment as "A-type LLJ's".

C-LLJ's are often referred to as the "dynamic pattern" because the low-level jet is coupled with the upper level jet which helps to increase precipitation, and occurs mostly in the spring/early summer (Chen and Wang 2009). Due to the trough, there will be lower-level convergence and upper-level divergence in the atmosphere to help promote upward motion along with the presence of the LLJ. A-LLJ's are more common during the middle to late summer as the upper-level anticyclone regime dominates with the onset of the North American Monsoon System in the Southwest United States (Loeffelbein 2008). Due to this monsoon system, there will be an associated lower-level low pressure over the southwestern United States, with a high pressure in the southeast. Thus, most of the atmospheric upward motion that would accompany the LLJ would be due to a shortwave around the 500mb-600mb level (Chen and Wang 2009). Although there are many differences in the synoptic setups associated with these two types of LLJ's, it is important that models are able to handle the differences and produce an accurate forecast.

d.) Related Research

The Great Plains LLJ is a commonly

researched topic, especially by colleges in the Midwest. However, most research performed on the LLJ aimed to look at the development and how precipitation is produced instead of directly looking at model accuracy. An example of this is from Gallus and Squitieri (2016), where they slightly analyzed precipitation accuracy of the LLJ, but mainly looked at how models forecasted the corresponding overnight mesoscale convective system that LLJ's tend to produce. Although this is a way to analyze forecast accuracy of the LLJ, it does not directly relate to LLJ strength or precipitation forecasts.

A study that has more directly looked at model precipitation forecasts was done by Loeffelbein (2008). He used data from 2005 and tested different models including the GFS and NAM-ETA, determining that models tended to be better at predicting precipitation events for C-type LLJ's when compared to A-type (Loeffelbein 2008). However, this study was performed with data from 2005 and earlier, and the NAM-ETA model is no longer in use, so it is important to perform a new analysis with the up-to-date models and recent events. Also, neither of these studies looked at LLJ precipitation over only Iowa, as they looked at the Great Plains as a whole.

This study used the current twelve kilometer North American Mesoscale model (NAM) in order to analyze the accuracy of precipitation forecasts over the state of Iowa during both C and A type LLJ schemes. The results will allow forecasters to better predict LLJ related events over Iowa by applying biases obtained during this research.

3. Data and Methodology

This study focused on the impacts of low-level jet influenced precipitation over the state of Iowa. It was also imperative to represent an equal number of cases with an upper-level tough (C-type) and upper-level anticyclone (A-type). Therefore, cases were selected based on a multitude of factors.

a.) LLJ Event Qualifications

For all cases, the timeframe of interest is between 0000UTC-1200UTC the day of the event. This time was chosen due to the LLJ being an overnight phenomena, so the precipitation formed must be during the evening to overnight hours. Another requirement for this study was the lack of contamination by ongoing precipitation over the state at the beginning of the 0000UTC period. In particular, it was important to avoid events with ongoing thunderstorm activity as this could lead to outflow boundaries that could influence the formation of future precipitation. This ensures that the precipitation seen from 0000UTC-1200UTC is formed due to influence by the LLJ. In not all cases was it possible to have the entire state clear of precipitation by the beginning of the period, but the ongoing precipitation was deemed to be non-influential to the occurrence of rainfall analyzed in this study.

It was also important to be able to distinguish actual low-level jet events in comparison to general strong wind events. To do this, the same criteria was used as in Loeffelbein (2008), where the wind event in question must have a discernable jet core, and a core minimum of at least 12 m/s. Any cases that did not meet this qualification were not considered.

b.) Grouping LLJ Events

Once a case was confirmed to be a LLJ, it was categorized into either an A or C-type LLJ. Again, this study used the same criteria as Loeffelbein (2008) when categorizing cases. For C-type cases, there must be an upper-level trough near or west of the Rockies at 300mb with a slight ridge associated east of the Great Plains. For A-type cases, there must be an upper-level anticyclone present in the central United States, from the 500mb-300mb levels. These anticyclones must be at least 10 degrees longitude in diameter to be considered for this study (Fig. 1). In both of these cases, the event must maintain the criteria for the entire 0000UTC-1200UTC period of interest. Using these categorizations, this study analyzed four cases from each the A and C-type LLJ's, totaling eight cases. The C-type dates were 5/11/11, 5/26/12, 4/27/14, and 5/8/16. The dates for the A-type cases were 6/24/15, 7/11/15, 9/17/15, and 6/22/16.

c.) Model Runs

This study focused on comparing the output of the North American Mesoscale (NAM) model to observations of precipitation and LLJ magnitude, location, and timing. This model has 12 km grid spacing, and had data available to use every three hours. For observations, the NAM analysis was used. This data also has 12 km grid spacing and is available in three hours increments, making direct comparisons possible. The NAM analysis provides a picture of the atmosphere through a combination of observations and previous model outputs, so although it is not observations alone, it still provides a clear picture of the atmosphere at times of interest (NOAA 2016).

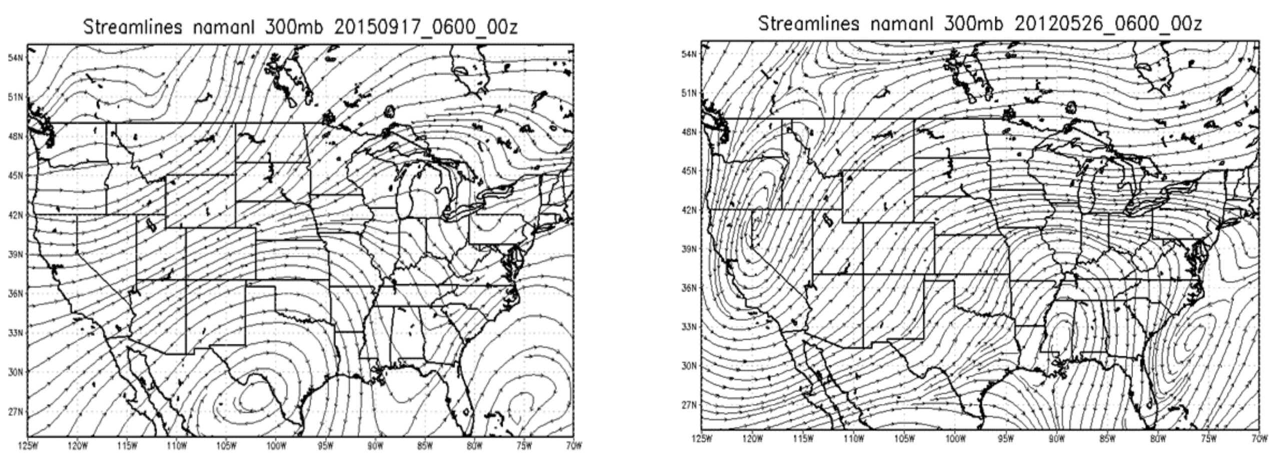


FIG. 1. Example NAM analysis 300mb streamline plots for both low-level jet synoptic regimes. A-type (left) shows an upper-level ridge on 9/17/2015 while C-type (right) shows an upper level trough in the western United States on 5/26/2012.

Using the NAM, there were two different model runs compared in this study. The first was the 0000UTC model run the day before the event (24 hours before event start) and the second was the 1800UTC model run the day of the event (6 hours before event start). These two model runs were chosen for the following three reasons. First, it gives an idea of whether the forecast of LLJ events get more accurate as time moves closer to the event start. Second, in the operational forecasting sector, the 1800UTC NAM run the day of the event is the last NAM model run that will be available for use before the event starts at 0000UTC. So, it is important to analyze the quality of that 1800UTC forecast as that will be the most recent model run that forecasters use to help them make their final pre-event forecast. And last is the influence of radiosonde data. Weather balloons are launched around the United States at 0000UTC and 1200UTC every day. So comparing a model run (0000UTC) that is directly after a balloon launch may lead to different results than a forecast without that observation data (1800UTC).

d.) Analysis Procedure: LLJ Location, Timing, and Magnitude

This model and analysis data were then used to plot the locations, timing, and magnitude of the LLJ cases. The files for the models were obtained from National Centers for Environmental Information (NCEI), available online for download. Data was only available in three hour increments, so analysis was taken at 0000UTC, 0300UTC, 0600UTC, 0900UTC, and 1200UTC. These were then used to plot streamlines at 300mb and 500mb in order to get a clear picture of the upper-level flow regime (Fig. 1). Next, isotach plots were overlaid with streamlines at 850mb as a representation of the LLJ direction and magnitude in m/s (Fig. 2).

The plotted data made it possible to be able to compare the peak magnitudes of the LLJ cases very easily. Data was collected comparing the 0000UTC forecast, 1800UTC forecast, and analysis (Fig. 3). For each case, the peak magnitude of the LLJ was sought after. If there was a time where two periods, say 0600UTC and 0900UTC, had the same peak magnitude, the time the magnitude was first observed was recorded, so 0600UTC in that example. Using this process, the peak magnitude, latitude, longitude, and timing of peak magnitude was recorded.

The main area of interest was the percent error of the magnitude of forecasted LLJ speed compared to the analysis speed. To

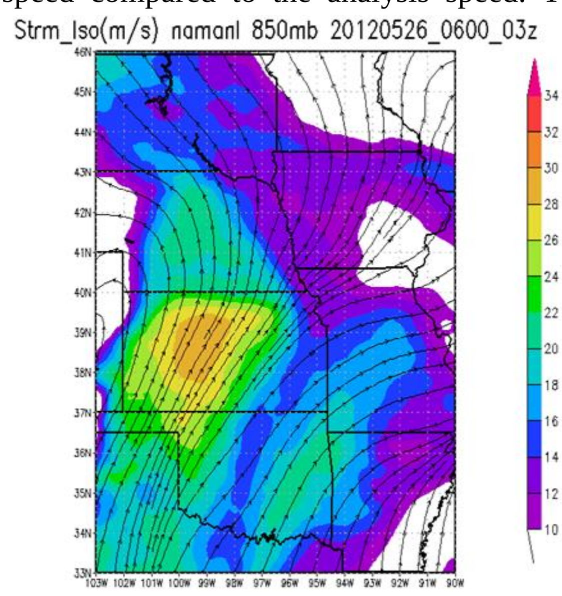


FIG. 2. Example NAM analysis 850mb plot of streamlines overlaid by wind speed (m/s) for the 5/26/12 C-type case at 0900UTC. Depicts an example of a LLJ, including the direction and magnitude of winds.

obtain these values, a percentage was calculated using ((forecasted wind speed – analysis wind speed) / (analysis wind speed)) * 100. This value was calculated for each case, which allowed for a calculation of average percent error per case. A 95% confidence level t-test was then used in order to determine if there was statistically significant error in the forecasts.

e.) Analysis Procedure: Precipitation

Forecasted precipitation accuracy also needed to be analyzed in conjunction with the LLJ forecast. The quantitative precipitation forecast (QPF) was mapped over Iowa for the full period from 0000UTC-1200UTC for each case. The NCEP Earth Observing Laboratory Stage IV data was used for observed precipitation amounts (UCAR 2016). The stage IV data is a combination of surface observations and radar estimated rainfall amounts, so it is able to cover the entire state of Iowa. These rainfall totals were also summed for the whole twelve hour period of interest for all cases.

In order to compare the NAM forecasts and the stage IV observations, the stage IV data needed to be re-gridded onto the same grid as the NAM 12km model. As a result, plots were made that calculated total error (in mm) over Iowa for each case studied. These plots show visually whether each case had an underforecast, overforecast, or neutral forecast for both model runs.

As was done for peak LLJ wind speed, a percent error was calculated for the peak forecasted rainfall amount of each model

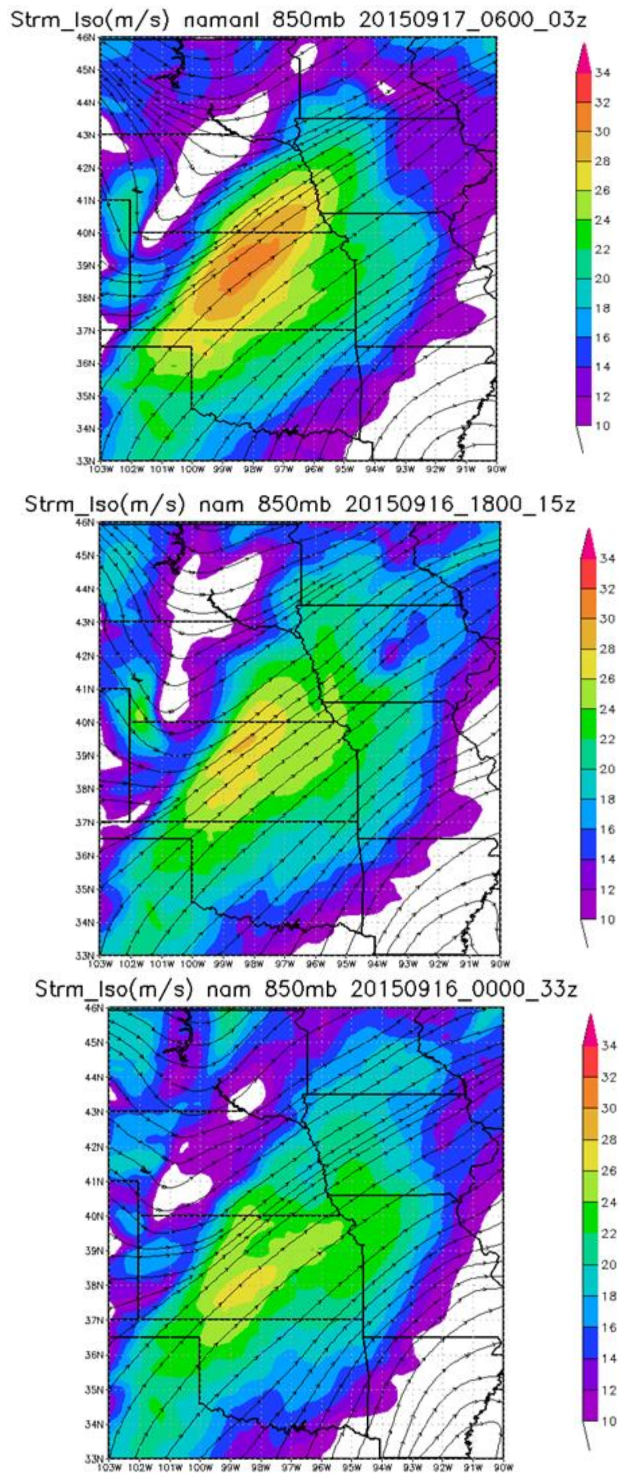


FIG. 3. Streamlines overlaid by the wind speed plots (m/s) for the 9/17/15 A–type event for the NAM analysis (top), 1800UTC forecast (middle), and 0000UTC forecast (bottom). All plots were at 0900UTC of the event in order to compare LLJ strength.

compared to the observation. A 95% confidence level t-test was again used in order to determine significance of the findings. Using this information, as well as results about the LLJ magnitude, location, and timing, a more complete picture of each event is analyzed.

4. Results and Analysis

a.) LLJ Magnitude

All eight cases were analyzed to determine the time, location, and magnitude of the peak low-level jet from 0000UTC-1200UTC. The first analysis made was for the error in forecasted velocity of each LLJ. Upon analysis of the NAM 0000UTC model run for all eight cases, the peak LLJ magnitude forecast was, on average, underforecasted by about -4.6% per event. The NAM 1800UTC model run resulted in a very similar percent error, which averaged an underforecast of about -4.4% per event (Fig. 4). However, these values did not result in a significant source of error, as the t-values for the 95% confidence test were well above the significance threshold (Appendix E).

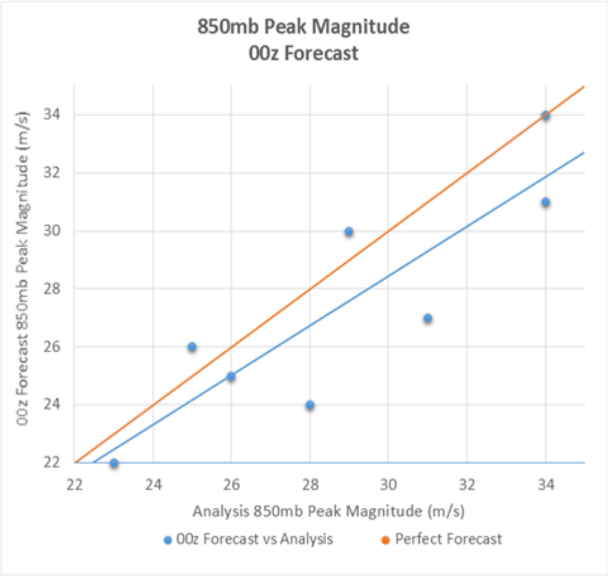
The cases were also broken down into their A and C-type categorizations and analyzed in the same way as above (Tables 1 and 2). Overall, there was more error in the C-type low-level jets as the 1800UTC forecast had around a -9.4% error per case while the 0000UTC forecast had about a -4.9% error per case, with both trending underforecasted. However, in all cases, there is too much variability in the results, so no t-test proved significant results in error from either forecast model run in both the C and A-type cases (Appendix E).

b.) LLJ Location and Timing

Just as with the magnitude analysis, there was too much variability in the timing and location of the peak LLJ (Fig. 5 and Fig. 6) to be able to see significant bias trends from the model forecasts. Both the 0000UTC and 1800UTC models had some slight errors in these categories, but there was no statistical significance showing that one model run was better than the other. However, this does not mean that forecasts were always accurate. There was still some error with the timing and location that could impact forecast accuracy for cases individually, even if there is not a significant trend with either model run.

c.) Precipitation

The next variable analyzed was precipitation. First, the percent error was calculated for maximum rainfall amounts over the whole twelve hour event (Fig. 7). For all eight cases, with no regime dependence, the average error per forecast for the 0000UTC model runs was about -69.3%, signifying a severe underforecast in peak precipitation. For the 1800UTC model runs, the average percent error per case was worse, at -75.4%, again signifying a large underforecast (Table 3). Based on t-tests at a 95% confidence level, both model runs showed statistically significant underforecasting of precipitation (Appendix F). In all, fifteen of the sixteen model runs between the 0000UTC and 1800UTC NAM resulted in an underforecast.



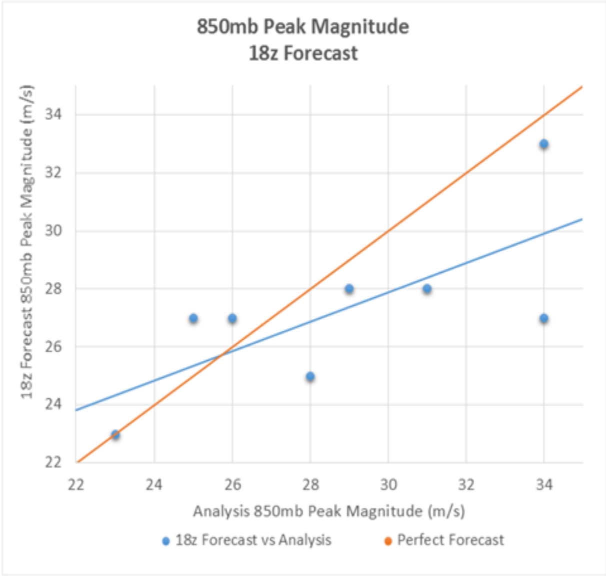


FIG.4. Scatterplot of NAM analysis peak LLJ magnitude (x-axis) vs NAM forecasted peak LLJ magnitude (y-axis) for the 0000UTC (left) and 1800UTC (right) forecasts. The orange line represents a perfect forecast with no error. The blue line represents the trend line of the model forecasts vs analysis. If a point is to the left of the orange line, that signifies an overforecast, while points to the right of the line signify an underforecast.

Tables 1 and 2. Tables of the model error for each case. Tables show individual error (mm), average error per case (mm), individual percent error, average percent error per case and standard deviation. The top table (Table 1) is C-type LLJ's, while the bottom table (Table 2) is A-type LLJ's.

C LLJ 850mb Peak LLJ Magnitude	18z Forecast - Analysis (m/s)	18z Percent Error (%)	00z Forecast - Analysis (m/s)	00z Percent Error (%)
4/27/2014	-1.00	-2.94	0.00	0.00
5/8/2016	-3.00	-10.71	-4.00	-14.29
5/11/2011	-7.00	-20.59	-3.00	-8.82
5/26/2012	-1.00	-3.45	1.00	3.45
Sum	**-12.00**	**-37.69**	**-6.00**	**-19.66**
Average Per Event	**-3.00**	**-9.42**	**-1.50**	**-4.92**
Standard Deviation	**2.83**	**8.25**	**2.38**	**8.11**

A LLJ 850mb Peak LLJ Magnitude	18z Forecast - Analysis (m/s)	18z Percent Error (%)	00z Forecast - Analysis (m/s)	00z Percent Error (%)
6/22/2016	1.00	3.85	-1.00	-3.85
6/24/2015	2.00	8.00	1.00	4.00
7/11/2015	0.00	0.00	-1.00	-4.35
9/17/2015	-3.00	-9.68	-4.00	-12.90
Sum	**0.00**	**2.17**	**-5.00**	**-17.10**
Average Per Event	**0.00**	**0.54**	**-1.25**	**-4.27**
Standard Deviation	**2.16**	**7.56**	**2.06**	**6.91**

There was only one accurate precipitation magnitude forecast, which was the 0000UTC run for the 4/27/14 case (Table 3).

The data was then broken down into the A-type and C-type categorizations to determine if one regime had more accurate forecasts than the other. For the C-type regimes, the 0000UTC model run had an average percent error of -64% per case, while the 1800UTC run was about -72%. The 0000UTC model results for the C-type regime are not quite strong enough to show statistically significant underforecasts, while the 1800UTC model run does (Appendix F). This implies a slightly better forecast accuracy for the 0000UTC model runs during C-type LLJ events.

The same process was also applied to the A-type regime cases. The average percent error for the 0000UTC model runs was -74.6% per case, while for the 1800UTC models runs it was about -78.9%. Analysis shows that both model runs had statistically significant error during cases with an anticyclone dominating the upper-levels (Appendix F). Also, the numbers are so similar between the two different model runs that it is not possible to

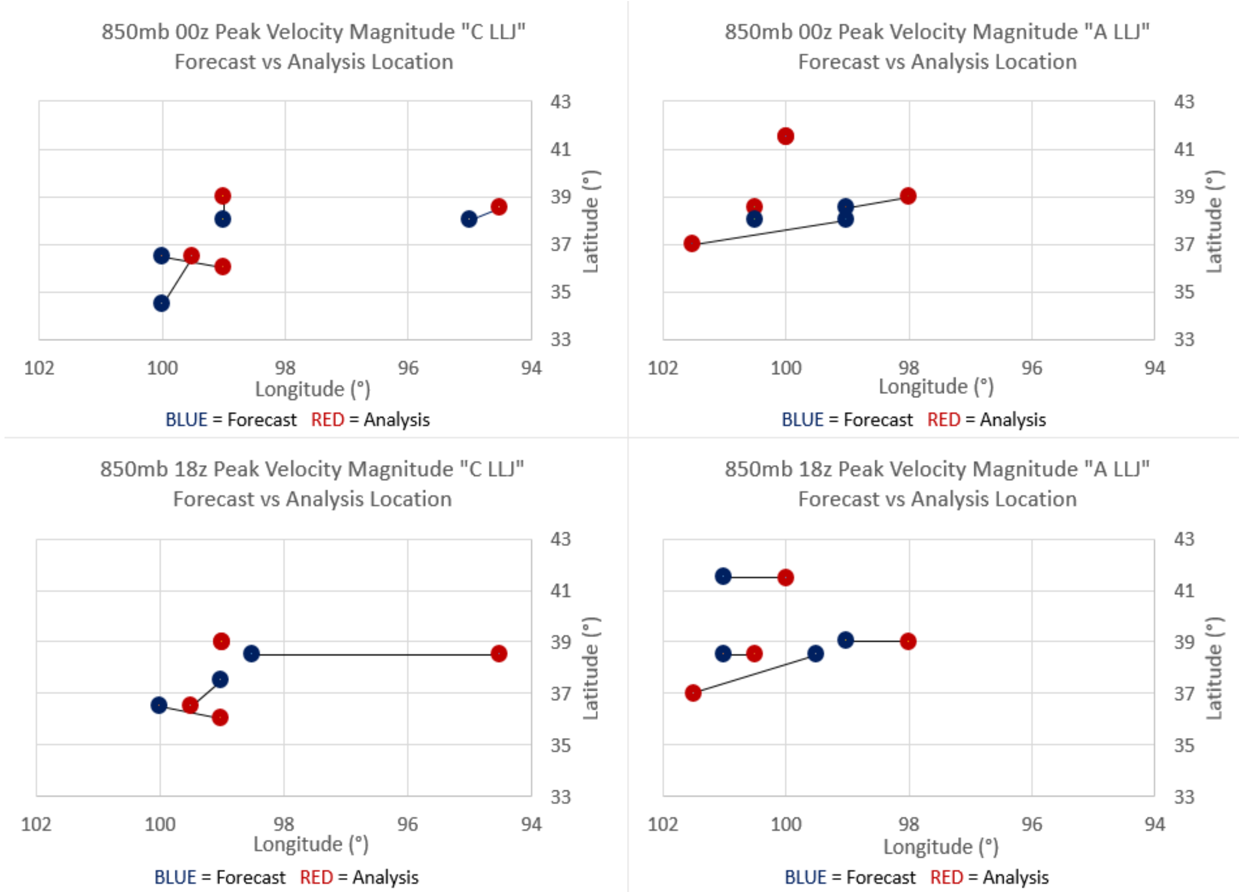


FIG. 5. Plots of the forecasted latitude and longitude peak LLJ magnitude vs the analysis. It was broken down into C-type 0000UTC model run (upper left), C-type 1800UTC model run (lower left), A-Type 0000UTC model run (upper right), and A-type 1800UTC model run (lower right). The forecasted locations are the blue dots while the analysis locations are the red dots. An event where the location was forecasted perfectly shows up as only a red dot.

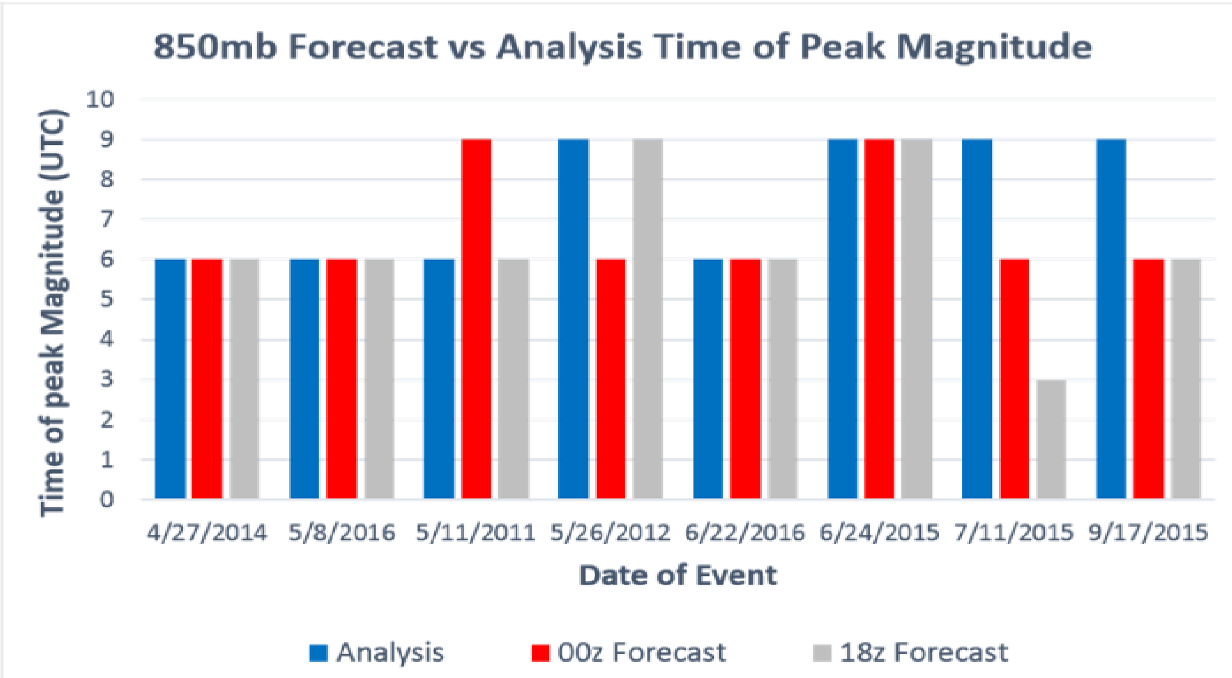


FIG. 6. Bar chart showing the timing of peak magnitude of each LLJ case. Each case has one bar for the NAM analysis (blue), 1800UTC forecast (grey), and 0000UTC forecast (red). Time options were only available every three hours from 0000UTC-1200UTC.

determine if one model run tends to have more accurate forecasts than the other.

Model precipitation error was also calculated throughout the entire state of Iowa (in mm) (Fig. 8). Analysis was then performed without taking magnitude into account, only analyzing the total area of under versus overforecasted values for each event. In total, thirteen of the sixteen model forecasts had a total area underforecast throughout the state, with only three forecasts that had a total area overforecast. This analysis was performed due to the NAM model runs having 12km grid spacing. This does not allow for the model to be able to have extremely high resolution forecasts, so it was possible that the QPF could have been spread out over a greater area. However, this analysis showed that both the 0000UTC and 1800UTC model runs underforecasted overall magnitude and area of rainfall on a consistent basis in both regimes.

5. Conclusion and Discussion

This study aimed to analyze low-level jet influenced overnight convection cases over Iowa and how the NAM 12km model forecasts them. The aspects analyzed included the magnitude, timing, and location of the LLJ, as well as precipitation from 0000UTC-1200UTC during each event. Overall, the NAM 0000UTC (24 hours prior to event) and 1800UTC (6 hours prior to event) did a fairly good job of forecasting the strength of the LLJ. They both averaged an underforecast, but neither was statistically significant. The same can be said regarding location and timing forecasting. There was some error from case to case, but nothing substantial enough to warrant consistent failure from either NAM model run or regime.

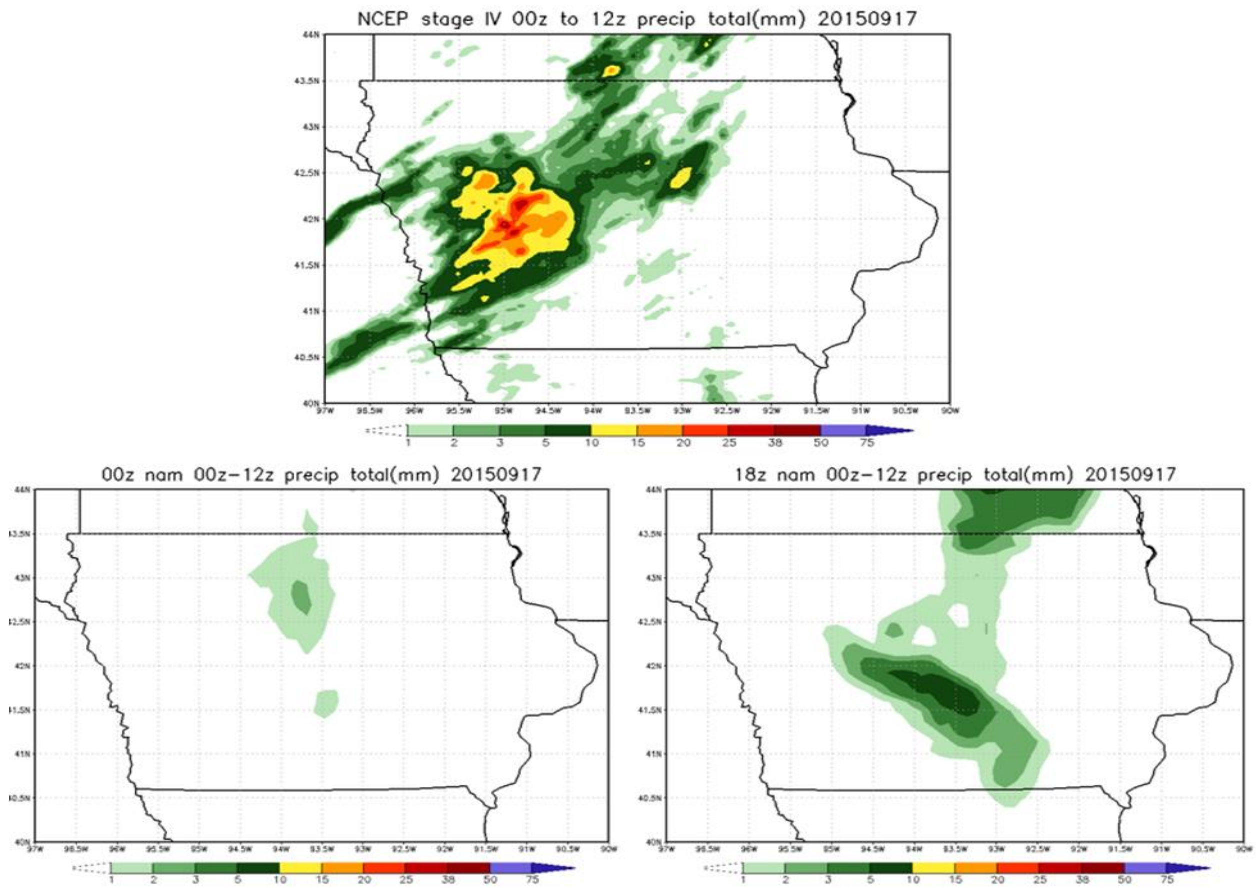


FIG. 7. Total precipitation plots from 0000UTC-1200UTC of the 9/17/15 A-type event (mm). Shown are the NCEP Stage IV rainfall accumulations (top), the 0000UTC NAM forecast (lower left), and the 1800UTC NAM forecast (lower right).

Table 3. Table for the total and percent error for the 0000UTC and 1800UTC NAM forecasts. The first two columns calculate the forecasted minus observed error for each case (in mm). The last two columns calculate a percent error for each case. The table also shows the sum, average per event, and standard deviation for each column.

00z-12z Peak Precip Magnitude	18z for-obs (mm)	00z for-obs (mm)	18z Percent Error (%)	00z Percent Error (%)
4/17/2014	-5.00	0.00	-50.00	0.00
5/8/2016	-7.00	-9.00	-70.00	-90.00
5/11/2011	-20.00	-20.00	-80.00	-80.00
5/26/2012	-44.00	-43.00	-88.00	-86.00
6/22/2016	-50.00	-58.00	-62.50	-72.50
6/24/2015	-47.00	-36.00	-94.00	-72.00
7/11/2015	-67.00	-48.00	-85.90	-61.54
9/17/2015	-19.00	-24.00	-73.08	-92.31
Sum	**-259.00**	**-238.00**	**-603.47**	**-554.35**
Average Per Event	**-32.38**	**-29.75**	**-75.43**	**-69.29**
Standard Deviation	**22.63**	**19.96**	**14.55**	**29.84**

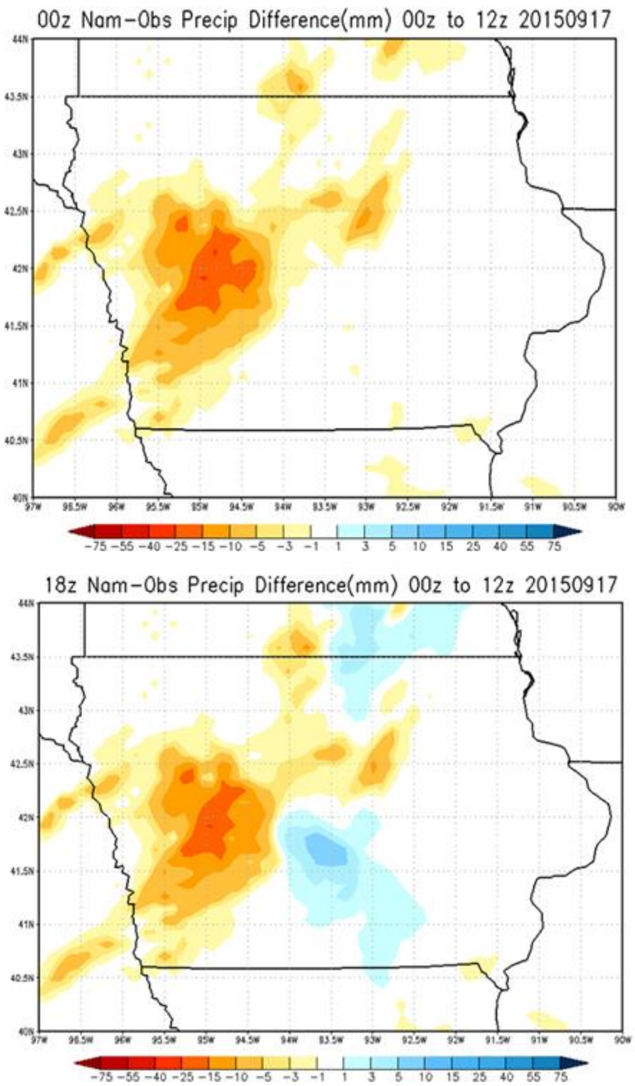


FIG. 8. Plots of NAM forecasted precipitation minus observed Stage IV data (mm) for the 9/17/15 A-type event. Shown is the 0000UTC forecast (top) and the 1800UTC forecast (bottom). Red colors indicate an underforecast while blue colors indicate an overforecast.

However, where there was a significant shortfall from the NAM model were the quantitative precipitation forecasts (QPF). These forecasts were constantly underforecasted, with fifteen of sixteen model runs producing an underforecast. Many were underforecasted by a significant amount as well, with eight of the sixteen total cases having at least been 80% underforecasted. Comparing the two models during different synoptic scale regimes, the A-type LLJ cases were significantly underforecasted, with both models statistically significant in their underforecasts. The slight difference lies in the C-type regime. Although both models, on average, had a large problem underforecasting precipitation, the 0000UTC model runs were not statistically significant in their underforecasts, while the 1800UTC model runs were. This points to a slightly more accurate forecast for upper-level trough LLJ events from the 0000UTC NAM when compared to the 1800UTC. This is a concerning result as this is most likely the last model professionals, such as the National Weather Service, will use before they put out their final event forecast. As for the regime dependence, these results point to slightly more accurate precipitation forecasts for C-type LLJ cases than A-type.

One thing that is interesting to note, none of the sixteen NAM forecasts produced a maximum rainfall output that resulted in an overforecast. Based on the results, this does not appear likely to be the fault of consistently underforecasting of the strength of the LLJ because there were no significant results confirming forecasting error. However, the NAM model runs are missing something when it comes to forecasting enough precipitation during LLJ events. It would be very interesting to look back at these cases again and explore more variables, including water vapor transport and convergence. If the NAM is under-representing the amount of convergence or water vapor transport that the LLJ supplies, it could very easily result in underforecasted precipitation amounts.

What has been shown is that the NAM 12km model has a problem forecasting precipitation in nocturnal low-level jet cases over Iowa. If there are no fixes made to this model, a forecaster should be aware of this bias and incorporate it into their forecasts until more information is found. If nothing changes, this model could continue to severely under-represent LLJ rainfall amounts, in which the impact can be felt all throughout Iowa.

6. Acknowledgements

I would like to thank Dr. Chen for his support throughout this entire process, and always being available if I had any questions. Also, thank you to Amanda Black and Paul Tsay for helping along the way with plotting issues.

7. References

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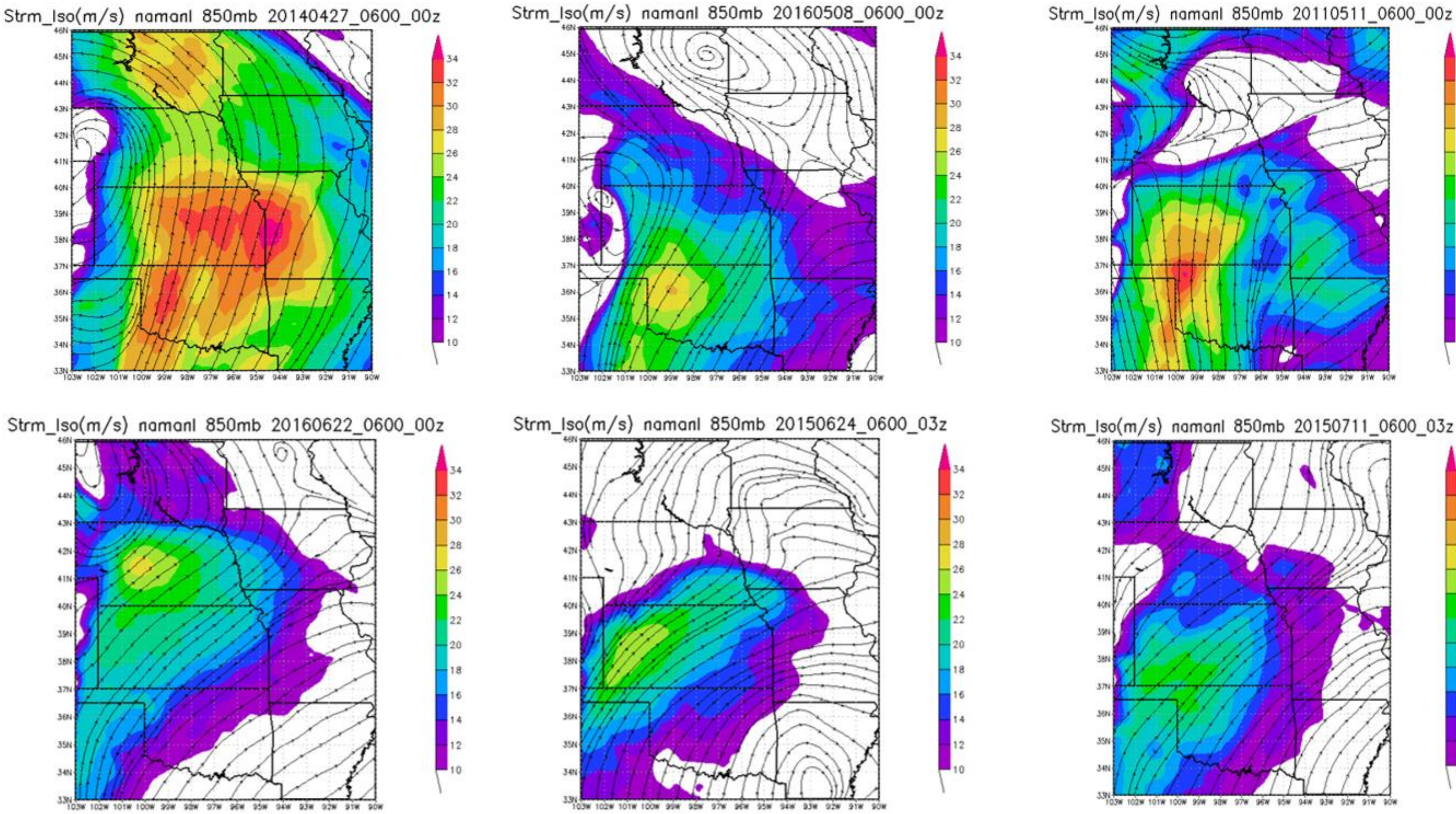
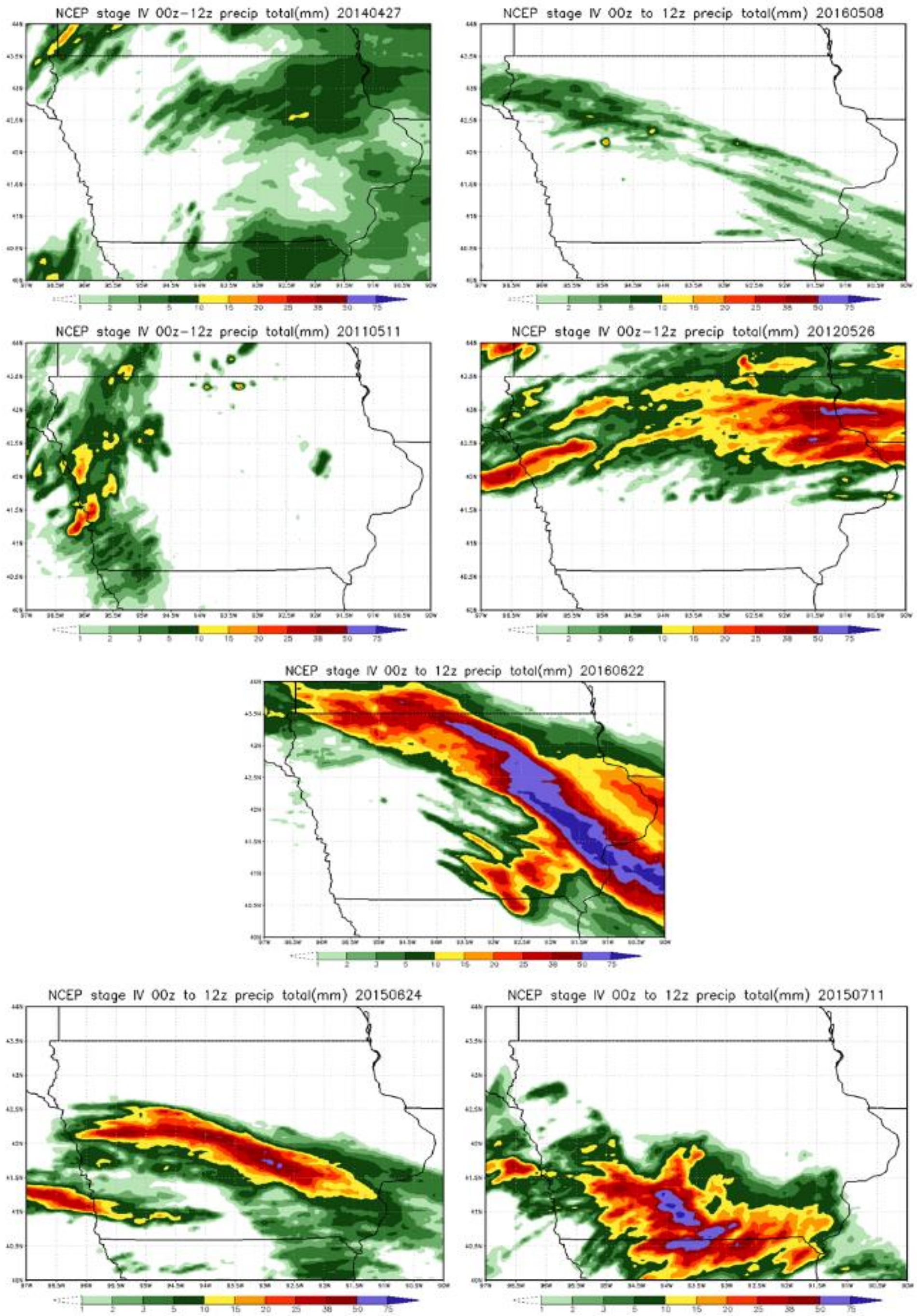
Appendix A



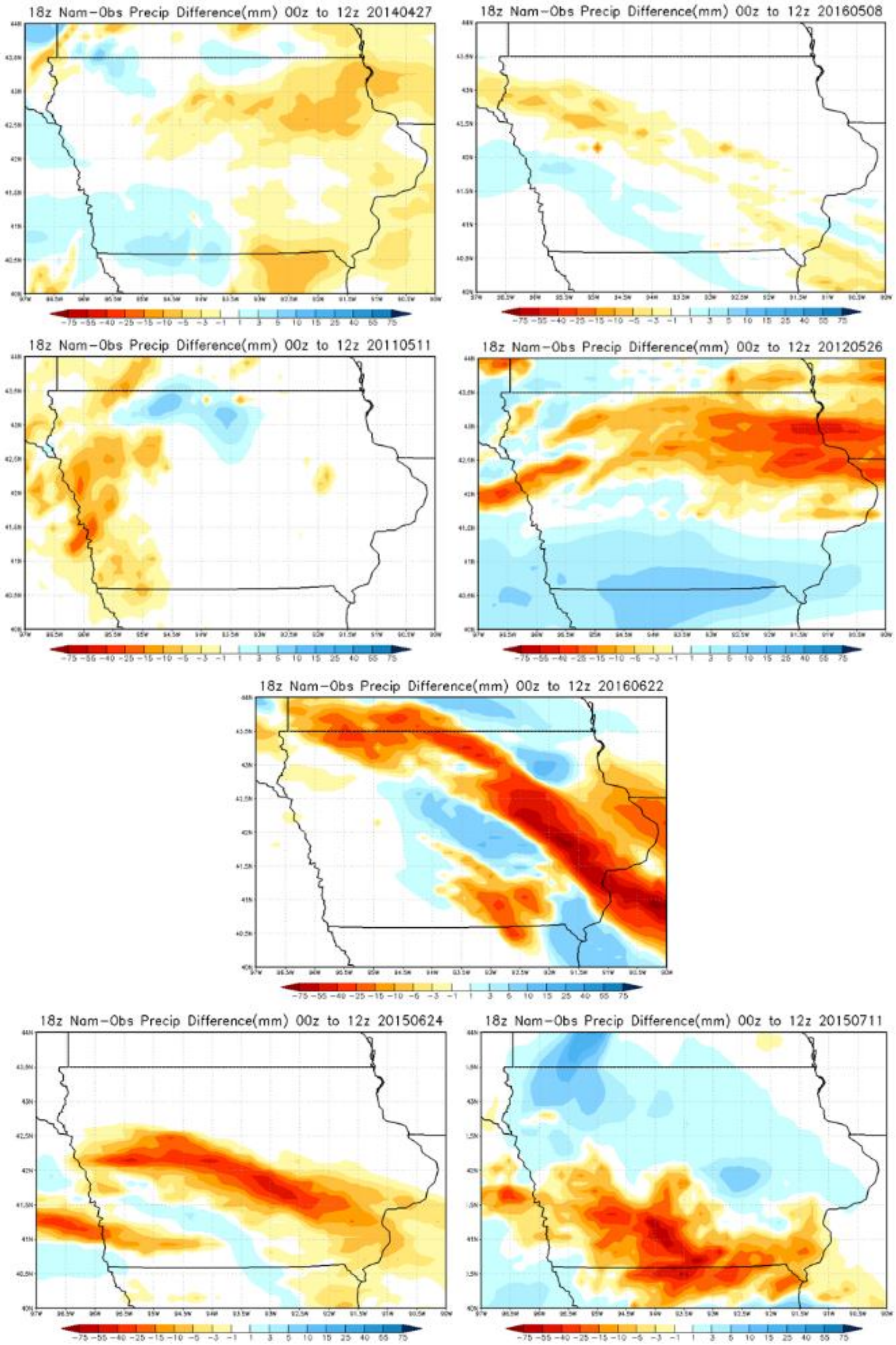
Appendix A. The remaining NAM analysis low-level jet cases that were not shown in the main paper. Plots include the peak wind speed (m/s) of each event overlaid by streamlines to show direction of flow. From upper left to lower right: 4/27/14, 5/8/16, 5/11/11, 6/22/16, 6/24/15, 7/11/15.

Appendix B



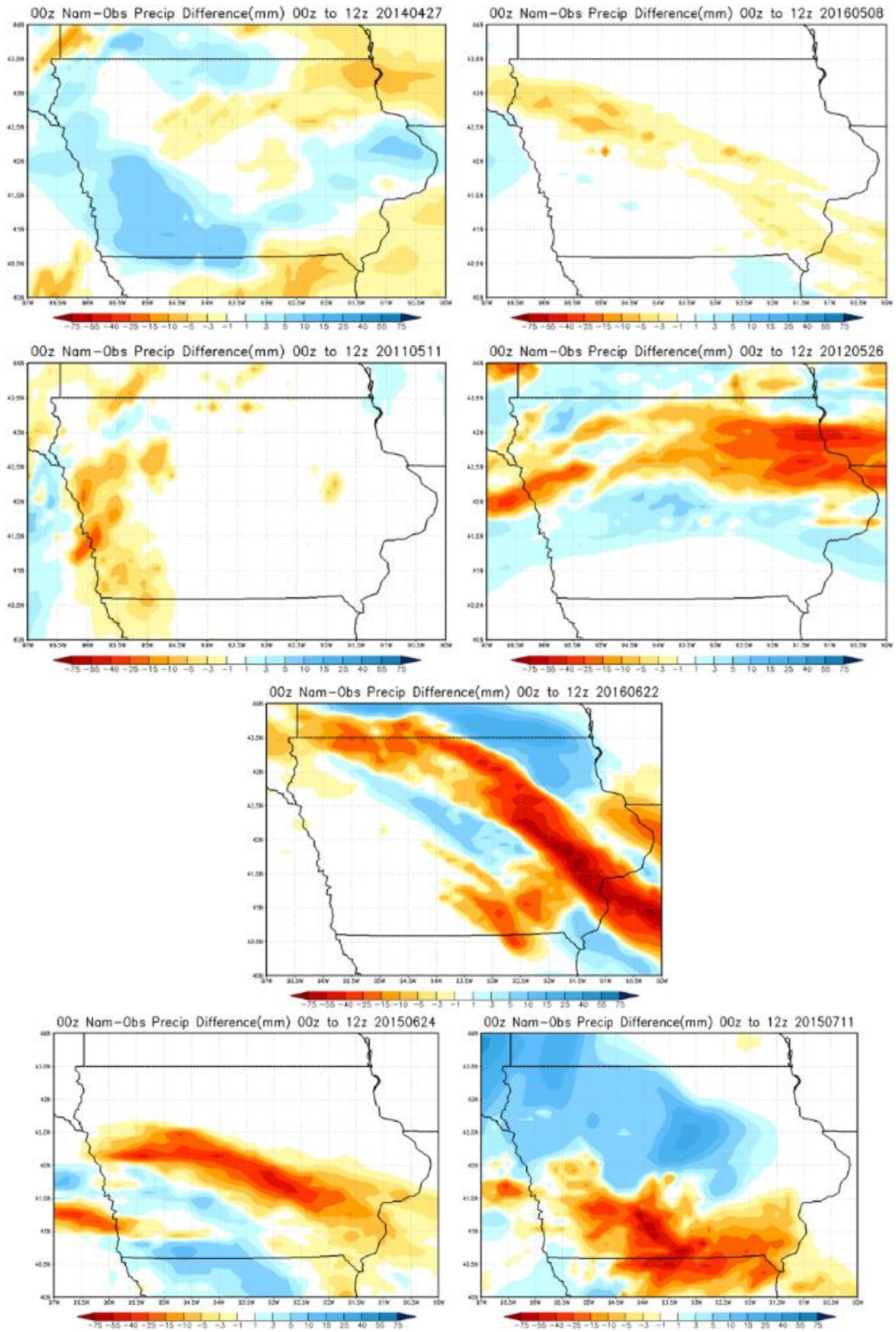
Appendix B. The remaining plots of NCEP stage IV precipitation data from 0000UTC-1200UTC for each case analyzed (mm). From upper left to lower right: 4/27/14, 5/8/16, 5/11/11, 5/26/12, 6/22/16, 6/24/15, 7/11/15.

Appendix C



Appendix C. Remaining plots of 1800UTC forecasted minus observed 0000UTC to 1200UTC precipitation totals (mm). From upper left to lower right: 4/27/14, 5/8/16, 5/11/11, 5/26/12, 6/22/16, 6/24/15, 7/11/15.

Appendix D



Appendix D. Remaining plots of 0000UTC forecasted minus observed 0000UTC to 1200UTC precipitation totals (mm). From upper left to lower right: 4/27/14, 5/8/16, 5/11/11, 5/26/12, 6/22/16, 6/24/15, 7/11/15.

Appendix E

LLJ Magnitude	00z Velocity	18z Velocity	A-type 18z Velocity	C-type 18z Velocity	A-type 00z Velocity	C-type 00z Velocity
t-value	0.105	0.208	0.895	0.1064	0.3039	0.312
Significant?	No	No	No	No	No	No

Appendix E. T-values from the t-tests at a 95% confidence level for LLJ magnitude percent error. If the value is <0.05 it is deemed significant, signifying a statistically significant error in the forecasts when compared to observations.

Appendix F

Precipitation	00z Precip	18z Precip	A-type 18z Precip	C-type 18z Precip	A-type 00z Precip	C-type 00z Precip
t-value	0.0003	<0.0001	0.0015	0.0031	0.0014	0.0583
Significant?	Yes	Yes	Yes	Yes	Yes	No

Appendix F. T-values from the t-tests at a 95% confidence level for precipitation percent error. If the value is <0.05 it is deemed significant, signifying a statistically significant error in the forecasts when compared to observations.